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FINITE ELEMENT (MARC) SOLUTION TECHNOLOGIES FOR VISCOPLASTIC ANALYSES

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INTRODUCTION

The drive for enhanced and improved performances of structural components operating at high temperatures, such as in aerospace and nuclear industries, has made a need for development of realistic constitutive models, accompanied by appropriate solution technologies for stress/life analyses of these components. The observed interaction between creep and plastic deformation at high temperatures has led to the development of a number of viscoplastic models. These models treat all inelastic strain as a single time-dependent quantity, and thus, automatically include creep, relaxation, and plasticity interactions.

Viscoplastic models provide a better description of inelastic behavior of materials, but their mathematical structure is very complex. The highly nonlinear and "stiff" nature of the constitutive equations makes analytical solutions difficult. It is, therefore, of the utmost importance that suitable solution (finite element or other numerical) technologies be developed to make these models adaptable for better and rational designs of components.

NASA Lewis has undertaken this important and challenging task. As a result of concerted efforts at Lewis during the last few years, several such solution technologies (in conjunction with the finite-element program, MARC, and other nonlinear structural analysis codes) have been developed and successfully applied to the solution of a number of uniaxial and multiaxial problems.

This paper describes some of these solution technologies and the models and presents representative results. The solution technologies developed and presented encompass a wide range of models, for example, isotropic, anisotropic, metal-matrix composites (with or without damage), and single-crystal (micromechanics) models.

It is believed that the solution technologies described herein will aid the designers and structural analysts in the stress/life analyses of components and will be exploited for better and rational component designs.

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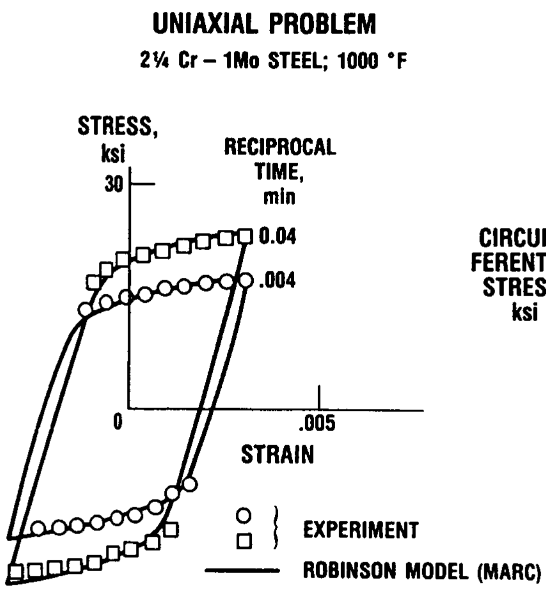
ROBINSON'S ISOTROPIC MODEL

The viscoplastic model developed by Robinson (Robinson and Swindeman, 1982) was implemented in the MARC general purpose, finite-element code (MARC Analysis Research Corp., 1983). Several uniaxial and multiaxial problems were solved to demonstrate the feasibility and applicability of the implementation as a useful structural analysis tool. Details of implementation are given by Cassenti (1983) and by Arya and Kaufman (1987). Two representative results are shown below.

A comparison of MARC and experimental hysteresis loops for the alloy 2¼Cr-1Mo steel at two strain rates is presented in the left plot. Excellent agreement between the MARC and experimental loops confirms the correct finite-element implementation of the model.

The right side of the figure provides an example of application of the implementation to the multiaxial problem of a thick-walled cylinder of 2¼Cr-1Mo steel under constant internal pressure at 800 °F. The circumferential stress redistribution in the cylinder after various periods of time is shown. The stresses were obtained using the finite-element implementation and a classical analytical solution. The good agreement between the two solutions indicates that the implementation can beneficially be utilized for other problems involving complex geometries and severe thermomechanical loadings.



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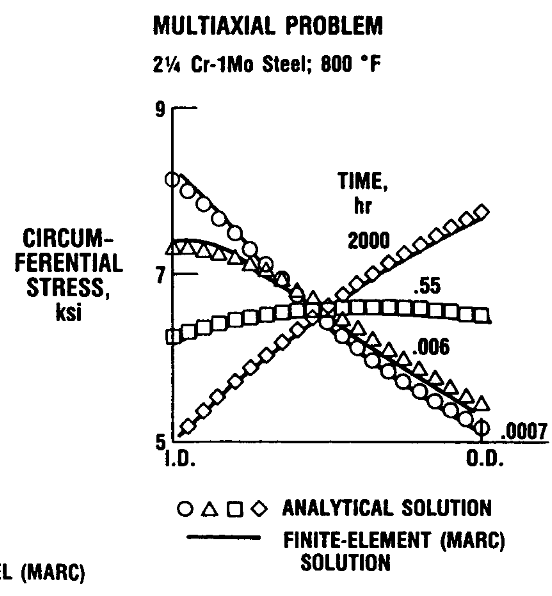

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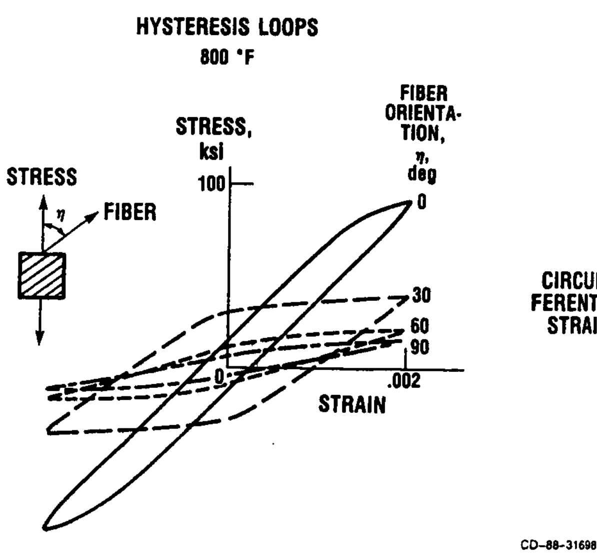
ROBINSON'S METAL-MATRIX COMPOSITE (ANISOTROPIC) CONSTITUTIVE MODEL

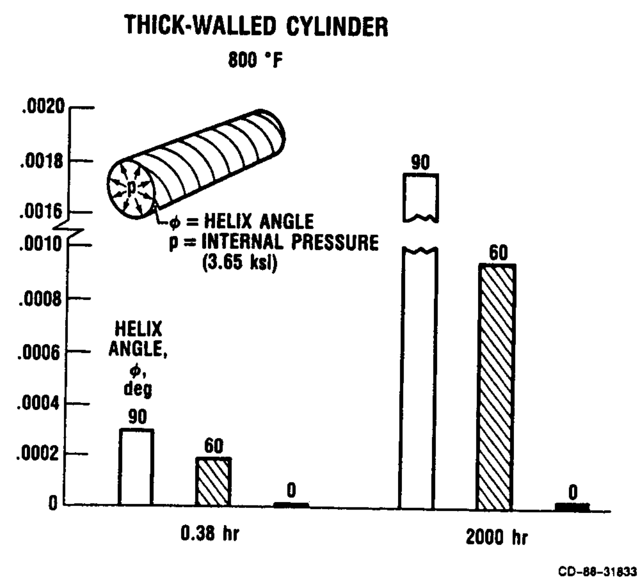
Because of their lightweight and enhanced strength, the metal-matrix composite materials are attracting considerable attention for high-temperature applications. As a result of concerted and leading efforts in this direction at Lewis, a metal-matrix composite viscoplastic model has been developed by Robinson and Duffy (1988).

To provide the designers and structural analysts with a complete finite-element package for the stress-life analyses, the above-mentioned model was implemented in MARC by Arya (1987). Several uniaxial and multiaxial problems were analyzed.

The stress-strain hysteresis loops shown below for different fiber orientations of tungsten fiber in a copper matrix are at a strain rate of 0.001/min at 800 °F. The loops reveal a considerable strength dependence on the fiber-loading angle.

The circumferential strains at the inner radius of a thick-walled metal-matrix composite cylinder at different times and fiber orientations are shown below. The cylinder is subjected to an internal pressure. As expected, the creep (inelastic) resistance of the cylinder can be greatly increased by placing the fibers in the circumferential direction, perpendicular to its axis.



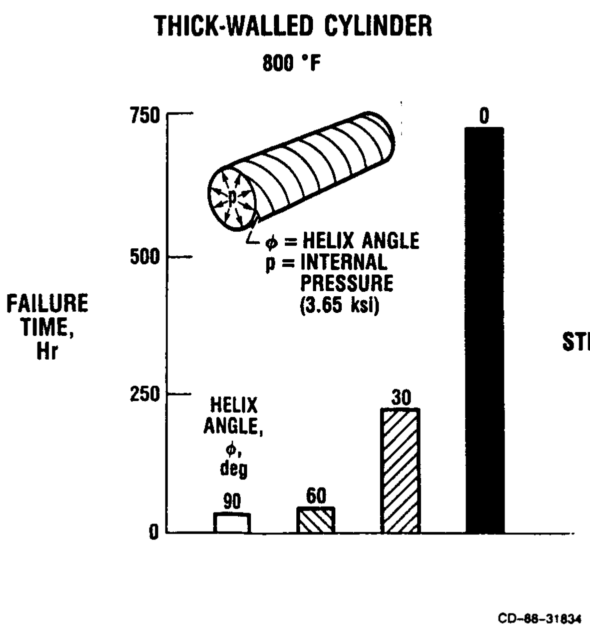


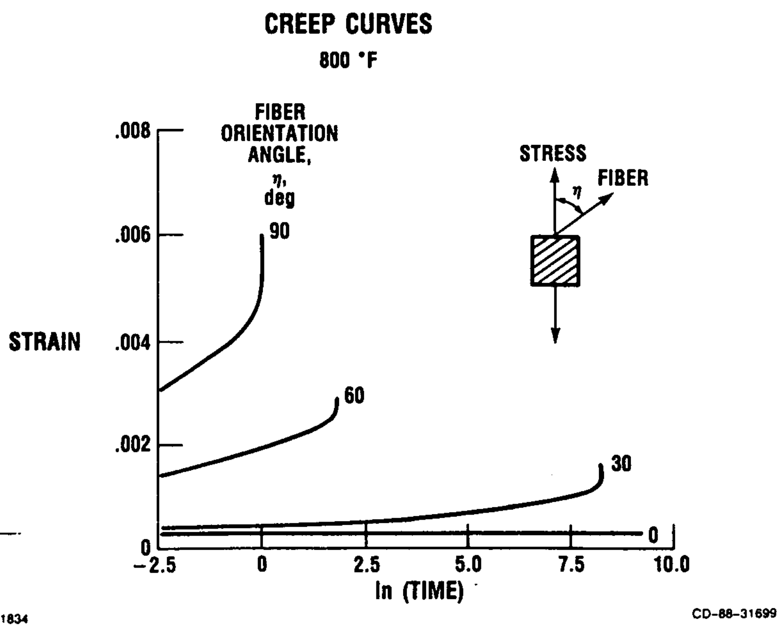
ROBINSON'S METAL-MATRIX COMPOSITE VISCOPLASTIC DAMAGE MODEL

The concept of damage evolution has recently been included by Robinson (personal communication, 1988) in the metal-matrix composite model described in the preceding section. This unique model has been implemented successfully in the MARC code. Two representative solutions have been obtained using the implementation as shown below.

The creep curves for constant axial stress including damage are shown for four fiber orientations. As expected, the minimum creep occurs when the load is applied in a direction parallel to the fibers.

Also shown is the time-to-failure for a thick-walled, internally pressurized cylinder for the same fiber orientation angles. As expected, the life of the cylinder can substantially be increased by orientating the fibers in the circumferential direction.





STOUFFER'S SINGLE-CRYSTAL CONSTITUTIVE MODEL

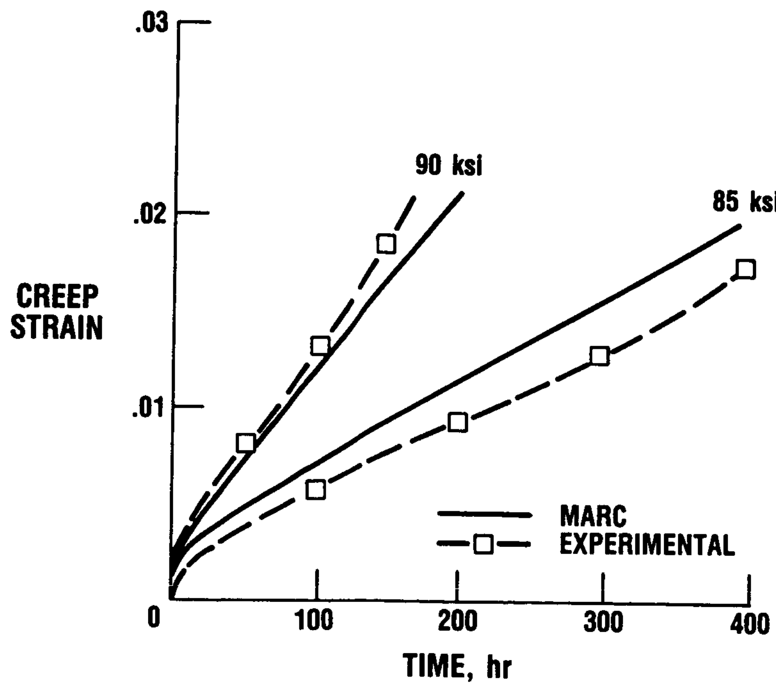
Conventionally cast polycrystalline superalloys, owing to the presence of grain boundaries, are susceptible to transverse grain boundary oxidation, corrosion and creep deformation, and subsequent cracking. The absence of grain boundaries in single-crystal alloys such as René-N4, MAR-M247, PWA 1480, has made them useful in gas turbine engines. A time-dependent, micromechanics, crystallographic viscoplastic model was developed by Stouffer (Dame and Stouffer, 1986) to characterize the inelastic behavior of single-crystal alloys.

To make the model applicable in the analysis and design of single-crystal components, it was implemented in the MARC code. Several uniaxial problems, including creep, relaxation, tensile, and cyclic loadings were analyzed.

A comparison is shown of MARC calculations and experimental creep curves at 1400 °F for the single-crystal alloy René-N4 in the direction [110]. The experimental values were taken from Stouffer (Dame and Stouffer, 1986). Good agreement is observed, which indicates the successful MARC implementation of the model.

A comparison of predictions and experimental uniaxial stress-strain hysteresis loops is also presented. The experimental values are again taken from Stouffer (Dame and Stouffer, 1986). Good agreement between MARC and experimental results encourages the use of this finite-element implementation for more complex loading conditions of more complex geometries.

CREEP CURVES
RENÉ-N4, [110], AT 1400 °F



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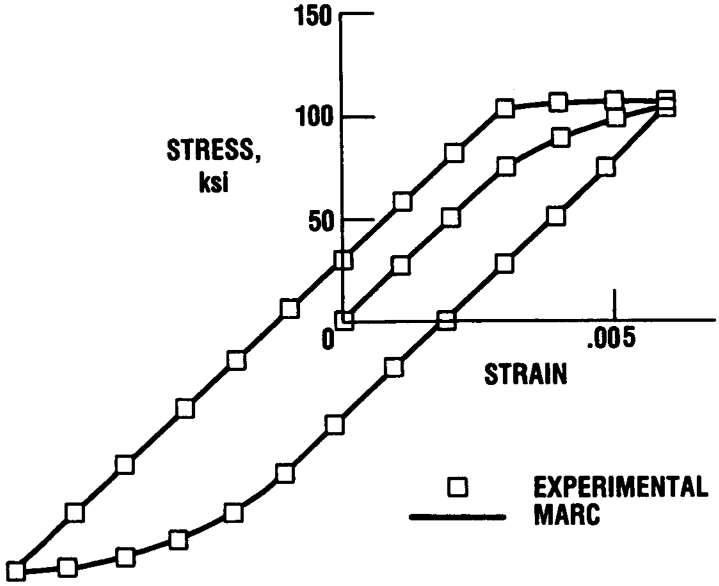
HYSTERESIS LOOP

RENÉ-N4, [110], AT 1400 °F



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